Chapter 4:

Tables and Figures

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Figure 4-1. Gold King plume as it moved through locations in the Animas River

Animas River at Silverton

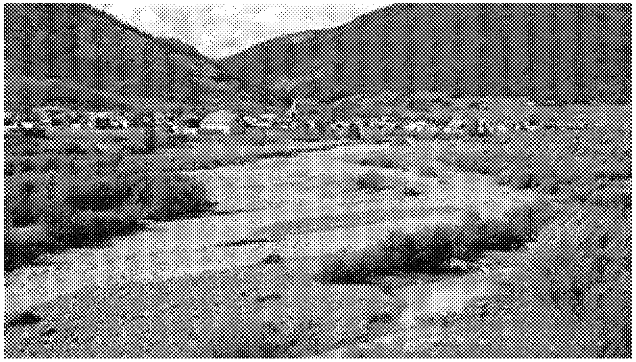

Photo: Denver Post.com

Meandering river reach north of Durango

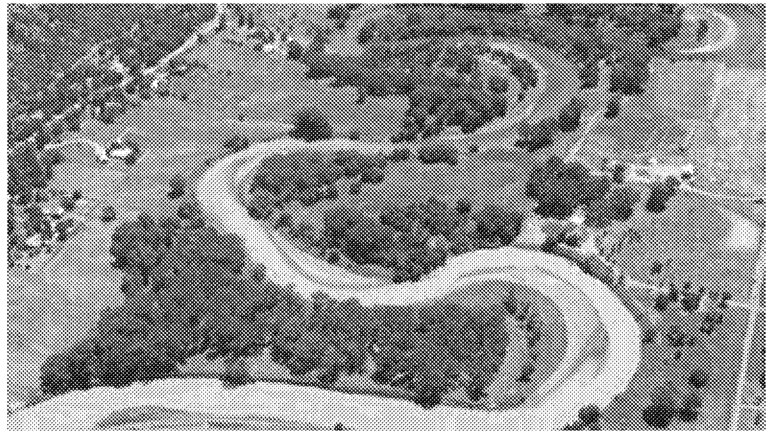

Photo: Bruce Gordon EcoFlight

In the Animas canyon in

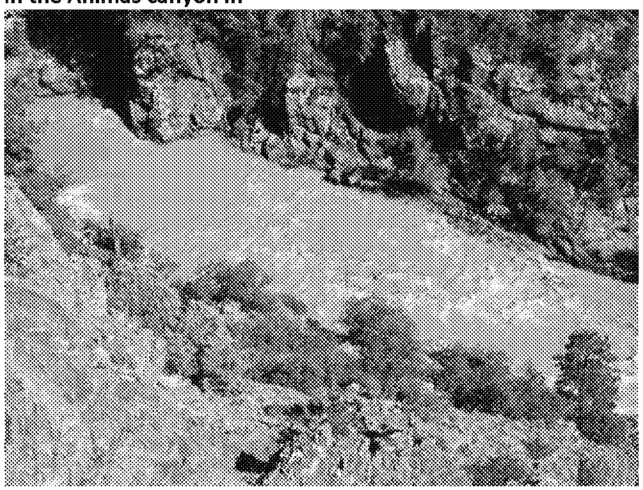

Photo: Mor,cCC BY – NC 2.0

On Southern Ute Indian Reservation (between 103 and 132 km for mine)

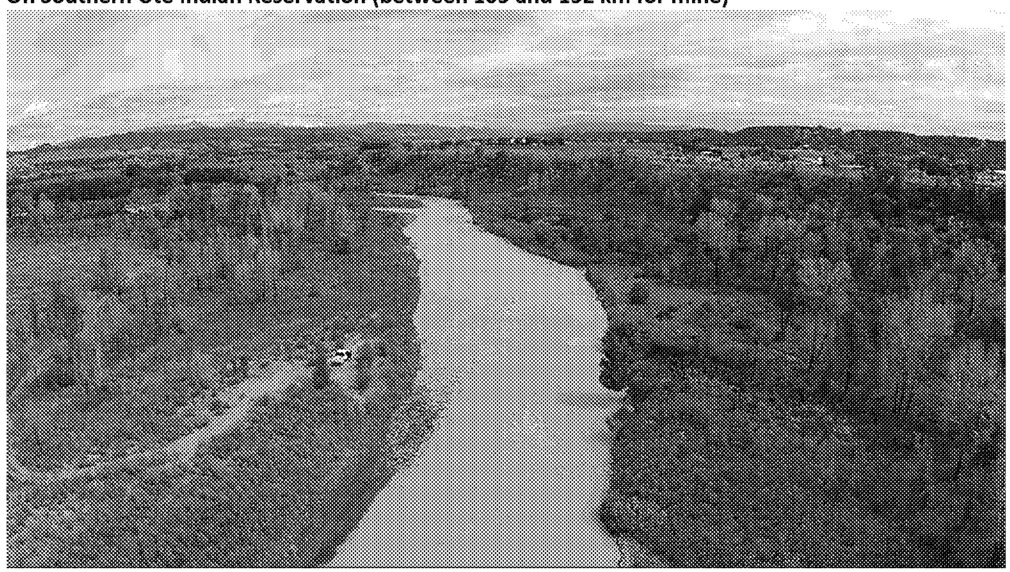

PHOTO: Southern Ute Indian Tribe

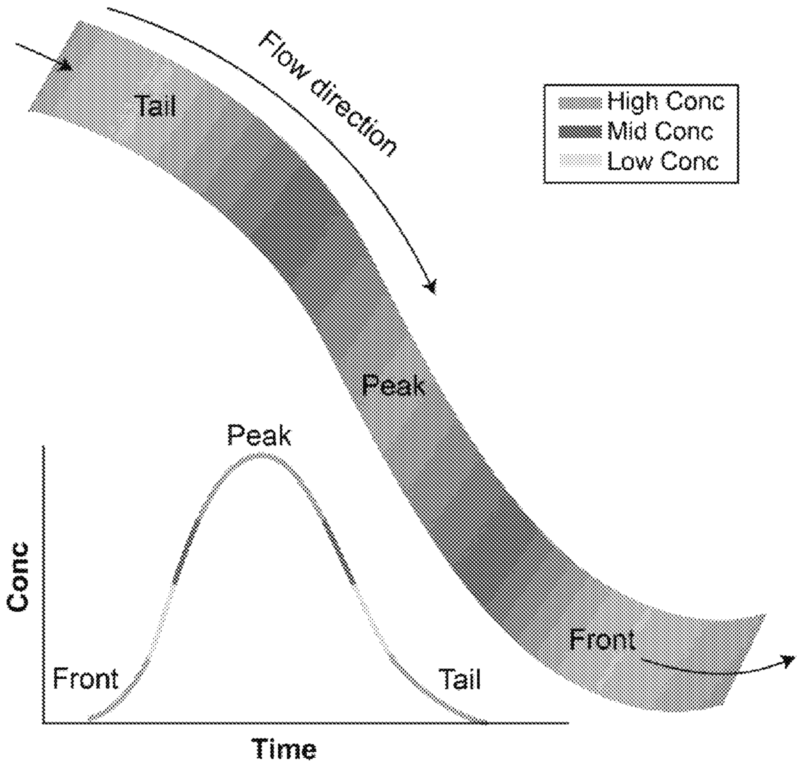

Figure 4-2. Conceptual drawing of what the plume was. The Gold King plume consisted of a slug of acid water with elevated with elevated concentrations of dissolved and colloidal/particulate metals possibly including entrained sediments that travelled as coherent mass through the Animas and San Juan Rivers. The plume had a beginning and end with peak concentration more or less in the middle. Plume characteristics changed as it moved through the rivers.

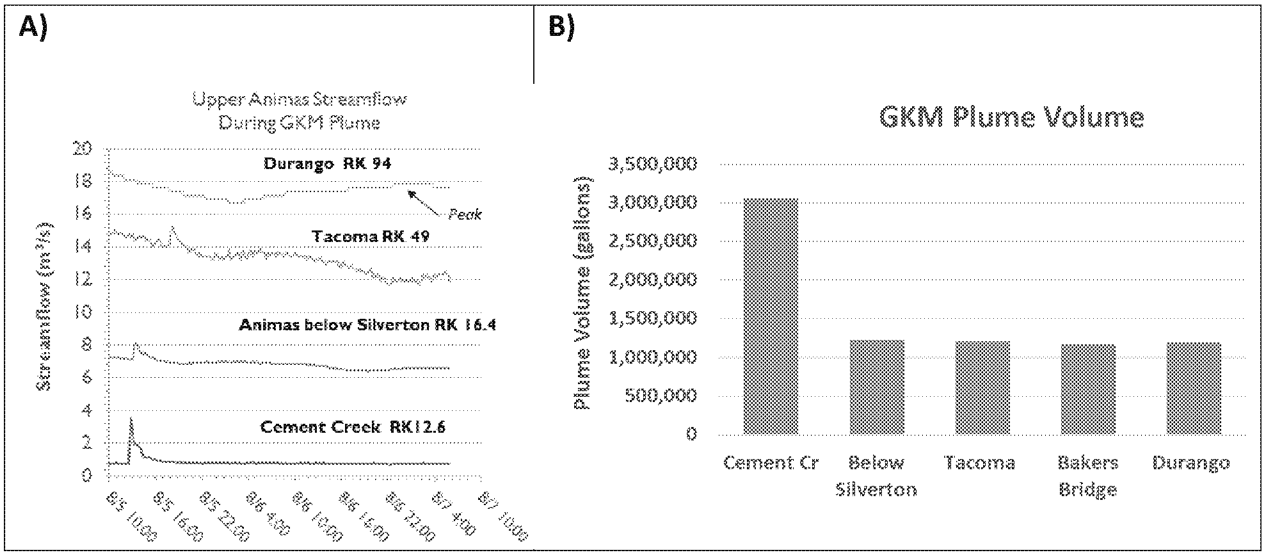

Figure 4-3. The Gold King metals load was carried in about 3,000,000 gals (11.36 x 10^6 liters) of acidic water released over a period of approximately eight hours. A) The water generated a wave that was measurable as a rise in water depth and streamflow volume at USGS stream gages in the headwaters of the Animas River. By Durango, the change in depth was very small and the wave was lost in the ambient river flow by the Cedar Hill gage. B) In the Animas River, the volume of water in excess of baseflow at each of the gages as the plume passed was approximately 1.2 million gals (4.54 x 10^6 L). This amount passed the Cement Creek gage in the first 45 minutes of the release.

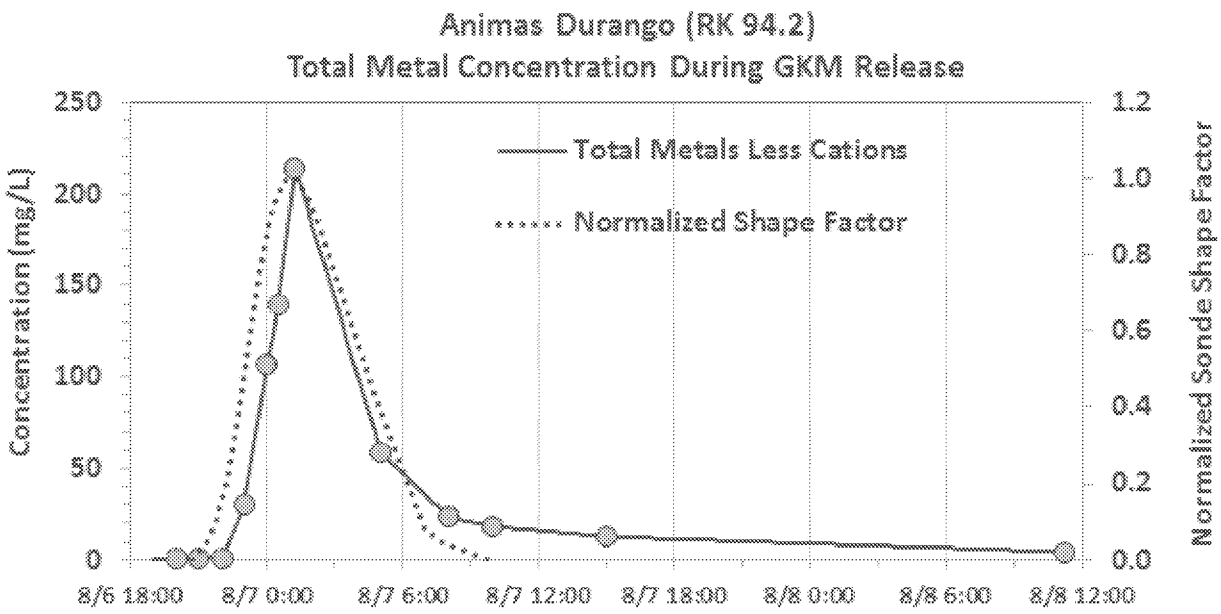

Figure 4-4. Observed characteristics of Gold King plume as it passed through Durango. The passage of the Gold King plume was well characterized by water sampling at Durango where the Mountain Studies Institute and The Rivers of Colorado Water Watch Network crews sampled from August 6 at 20:00 to August 7 at 9:30. Total summed metals are shown during the plume at two nearby sites coordinated by travel time. The rise and fall of the plume was rapid; return to background was slower as dispersion elongated the tailing edge. This site returned to pre-event conditions by August 8 (MSI 2016).

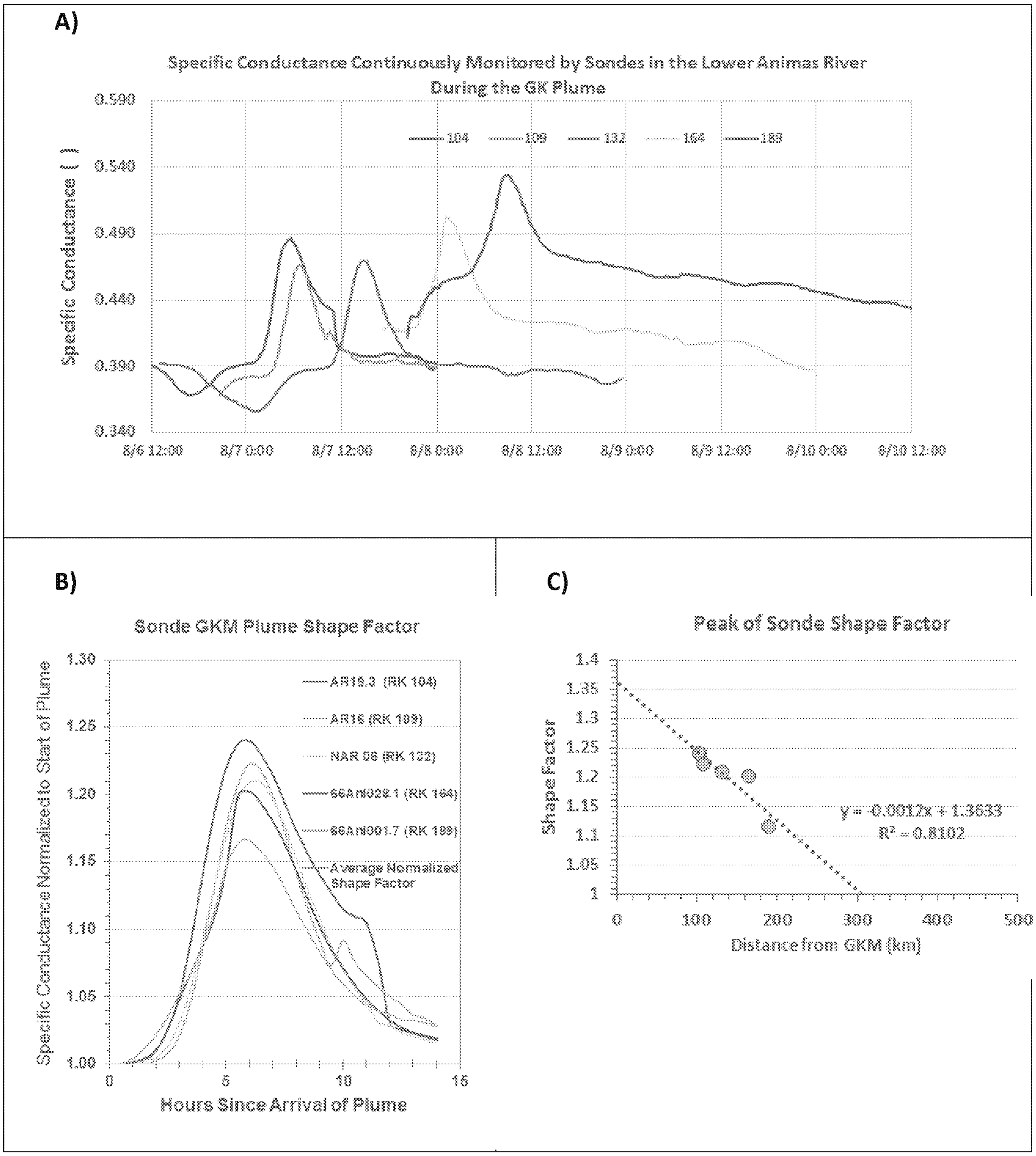

Figure 4-5. Plume movement was measured by continuously measuring sondes at five site in the lower Animas, specific conductance traces are shown in (A). Normalized sonde shapes determined by dividing each measure on the trace by the starting value (B). Peak normalized values decreased as the plume moved down river (C)

Table 4-1. Locations where the Gold King plume was empirically modeled. Sites are located near USGS gages and locations where water quality samples were routinely collected during the Gold King plume and in the months following. Water concentration data during plume movement were obtained from multiple providers at some sites. Metals in water or sediments have been monitored at some of these locations over time.

	Common Reference	State	Distance from Gold King Source (km)	Associated USGS Gage	Associated Sampling Sites
Cement Creek	Cement Creek	CO	12.5	9358550	EPAR8: 14th St. Bridge, CC48
Animas River	Silverton	CO	16.4	09359020	EPAR8: A72
	Bakers Bridge	CO	63.8	09359500	EPAR8: Bakers Bridge GKM02
	Durango	CO	94.2	09361500	EPAR8: GKM04 MSI: Rotary Park CO River Watch
	SUIT	CO	132.0	09363500	SUIT: NAR06
	Aztec	NM	164.1	09364010	EPAR6: ADW010 NMED: 66Animas028.1
	Farmington	NM	190.2	09364500	EPAR6: FW040 NMED:
San Juan River	Farmington NM	NM	193.0	09365000	PAR6: LVW020, SJLP NMED: 67SanJuan088
	Shiprock	NM	246.3	09368000	EPAR6: SJSR USGS gage
	Four Corners	UT	295.8	09371010	EPAR6: SJ4C UDEQ 160 xing
	Bluff, Sand Island	UT	377.1	09379500	EPA: SJBB UDEQ: Sand Island
	Mexican Hat	UT	421.5	09379500	EPA: SJMH UDEQ: Mex Hat

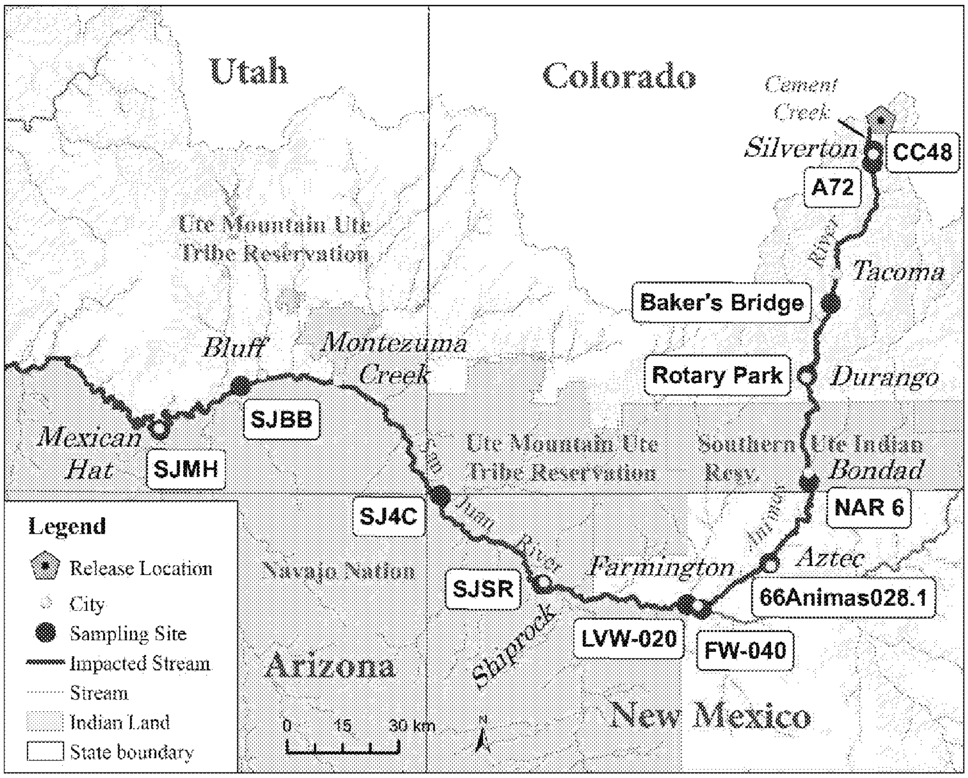

Figure 4-6. Empirically modeled plume locations. The Gold King plume was empirically modeled using observed water sample at 12 locations distributed within the Animas and San Juan Rivers. Sites were selected to be near USGS gage sites that were used to for flow and near sites that were routinely monitored during the passage of the plume.

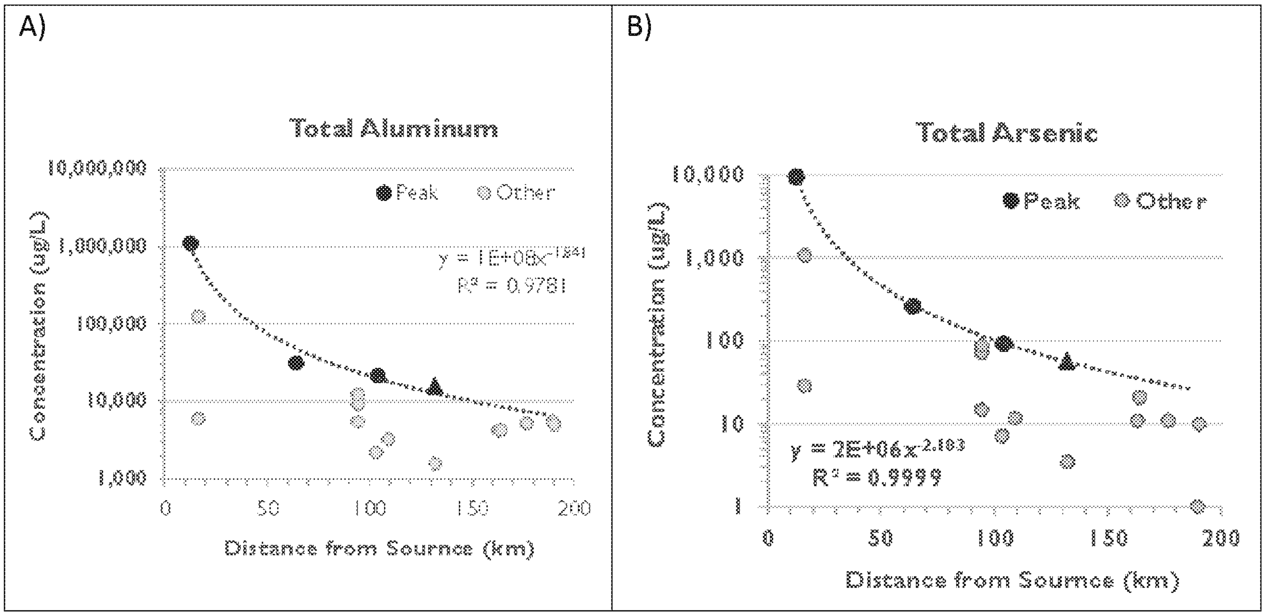

Figure 4-7.Determining peak concentration. The Gold King plume and its short duration peak passed by sampling locations quickly. Relatively few samples hit the peak of the plume. To reproduce the peak accurately at each site, it is essential to estimate the peak. Samples collected during plume movement are shown for two metals. Using a variety of techniques, samples near the peak are identified as red dots. A power regression was fit to these points beginning at an estimated sample at the Animas River junction with Cement Creek that mixes the Cement Creek estimated peak 50% with the Animas River.

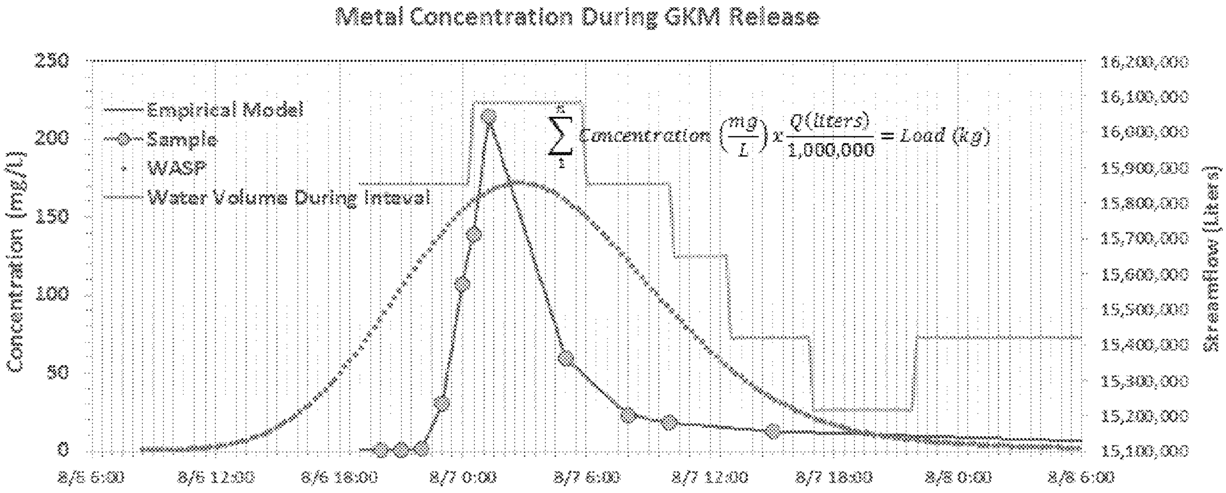

Figure 4-8. Schematic of plume reconstruction with observed water samples. Empirical plume modeling involved fitting fitting concentrations of 23 Target Analyte List (TAL) metals between sampled observations. Sampling during the plume was extensive at a few sites allowing direct connection of samples (A). At most sites sampling was infrequent during passage of the plume. (Sometimes limited to two samples. Various techniques were used to replicate the likely shape of the plume at an interval of 15-minutes to match USGS flow records. Continuous records of physical parameters such as pH, specific conductance and turbidity were recorded by instream sampling devices that helped define the timing and magnitude of the plume.

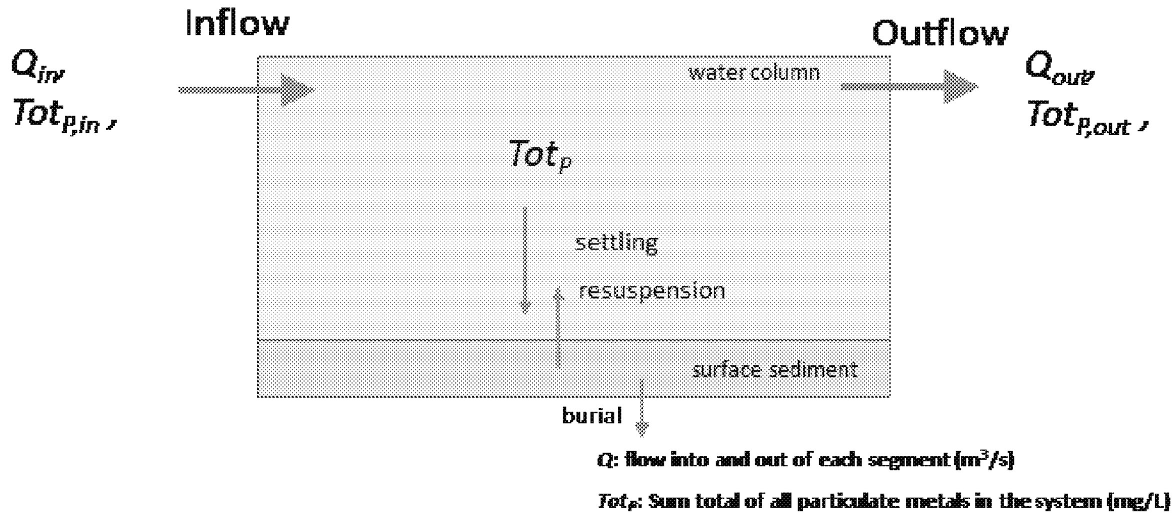

Figure 4-9. Gold King Mine plume transport conceptual mode. WASP was used to construct the GKM WASP Model to simulate the fate and transport of metals in the Animas and San Juan Rivers. This figure presents the processes used to represent total particulate metals in the system. We simulate total particulate metals, Tot_P, which can settle into the sediment and resuspend. Tot_P flow from the upstream segment and flow out to the downstream segment with the flowing water. Tot_P settles at the empirically determined settling rate, which is a function of how far the plume has traveled along the river. Each segment is simulated as a continuously stirred tank reactor.

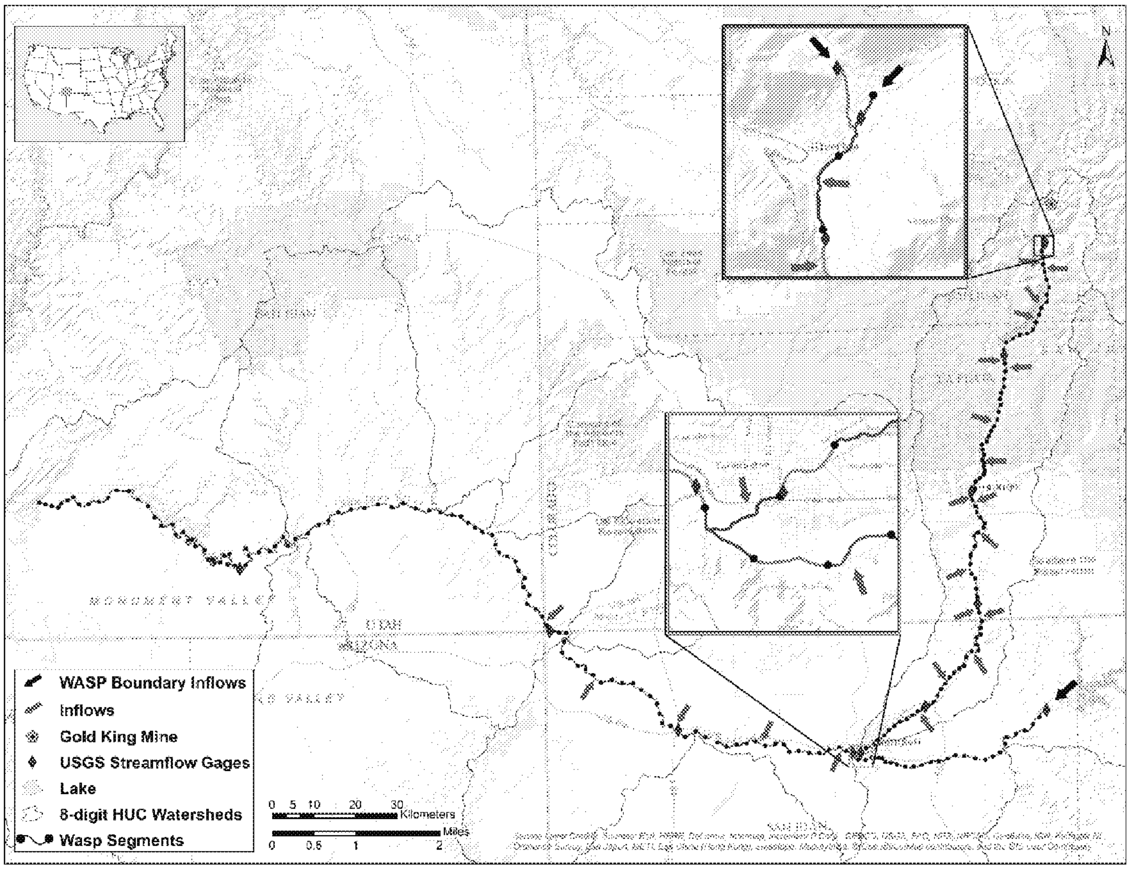

Figure 4-10. Model domain and setup for the GKM WASP Model. The model domain for the GKM WASP Model was constructed using BASINS to download NHDPlus and associated files to create the WASP segmentation. Here, the dots represent the division between the WASP segments. Each segment has a length, width, depth, and volume, but not necessarily consists of a rectangular shape. Black arrows represent boundaries with inflow concentrations. The black and blue arrows represent the inflows based on partitioning of USGS gages (red diamonds). There were 229 surface water and 229 sediment segments. Mean length was 2447 m, ranging from 922 to 4655 m. See Appendix B for more details on segment parameterization.

Table 4-2. WASP Parameterization, Calibration, and Data Sources. This table lists the different types of data required to implement WASP. For the different aspects of WASP, we pulled data from different sources. BASINS was used to pull GIS data and WASP Builder was used to take that data and construct the WASP Segmentation. More details on how this data was used to determine the parameterization is provided in Appendix B.

Parameter		Source
Stream Description	Segment Length, Width, Depth, Volume, Slope	BASINS, NHDPlus
Hydraulic Geometry	Velocity and Depth Exponent	USGS Gage Cross-section, Regression, Calibration
Bottom Roughness	Manning's Roughness	Calibrated
Stream Flow		USGS Gages
GKM Release Load		Estimated from Empirical Data
Settling Velocity		Estimated from Empirical Data
Partition Coefficients		Estimated from Empirical Data

Table 4-3. Synergy of plume modeling approaches. Comparison of modeling approaches used in this study to characterize the Gold King plume.

Empirical Model	GKM WASP Model
• Reconstructs plume at 12 locations based on observed data • Locations selected based on nearby USGS gages and availability of sampling data, often multiple agencies • Identifies plume based on flow, sondes, or with assistance of WASP • Computes concentrations for dissolved and colloidal/particulate solids from field sampled data as plume passes the site • Computes mass of dissolved and colloidal particulate solids as plume passes the site • Partitions between dissolved and colloidal based on sample data	• Water quality modelling software dynamically transports pollutants downstream from source • River segments ~ 2 km in length • Moves water from segment to segment adding water between gages • Suspends and deposits particles during transit according to velocities relative to particle size • Particle settling parameterized using metal mass developed by empirical model • Empirically calibrated to loads estimated by empirical model • Empirically partitions metals from dissolved to colloidal/particulate solids calibrated to sample data

Figure 4-11. Early in the plume as it began to move through this location on the Southern Ute Indian Reservation. The visible plume gained color quickly indicating the core of the plume arrived within a relatively narrow window of time.

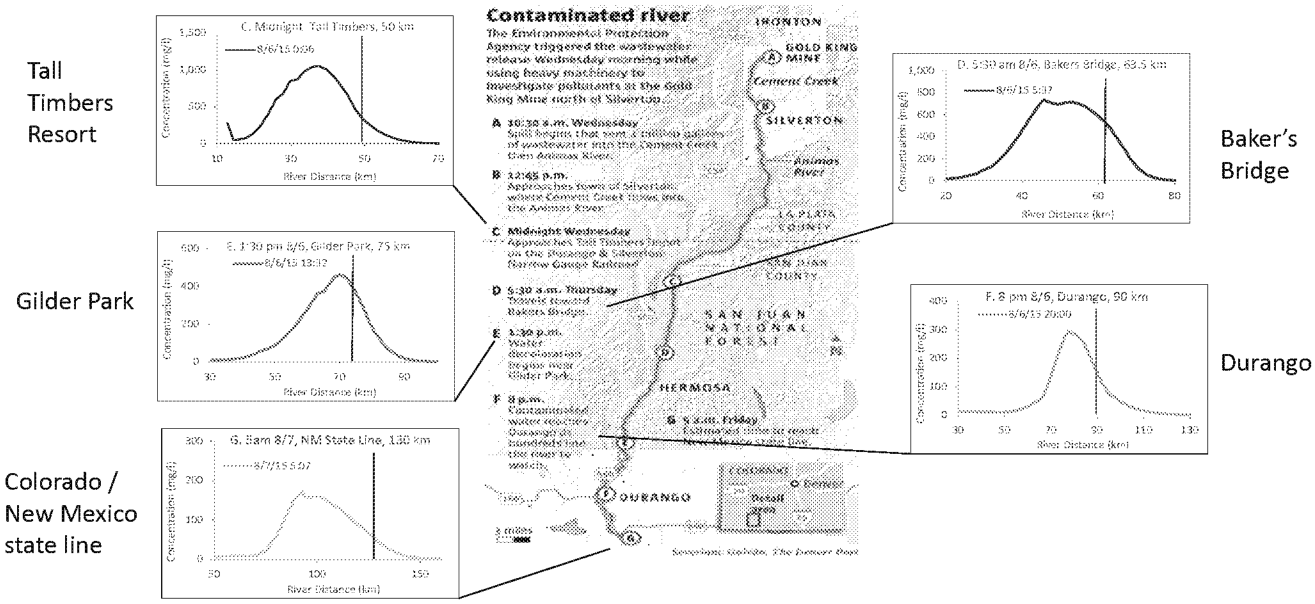

Figure 4-12. Orientation of model plume to visual observations. Simulated concentrations at a series of locations are compared to reported visual observations as an indication of what observers saw relative to what WASP modeled at that location. At each location, the concentration for a given reported time is plotted against river distance. The red line on each figure represents the location where there was a report of the plume or that the plume was approaching (See map for the report at that time for a given location). These figures show how for all locations the model simulation suggests that the concentration was already starting to rise before it was visually observed. That is, the mechanical dispersion caused the plume to move ahead, yet the concentration was lower than could be visually observed. Conversely, this means that the visual presence of the plume would subside, yet the concentrations may still be elevated.

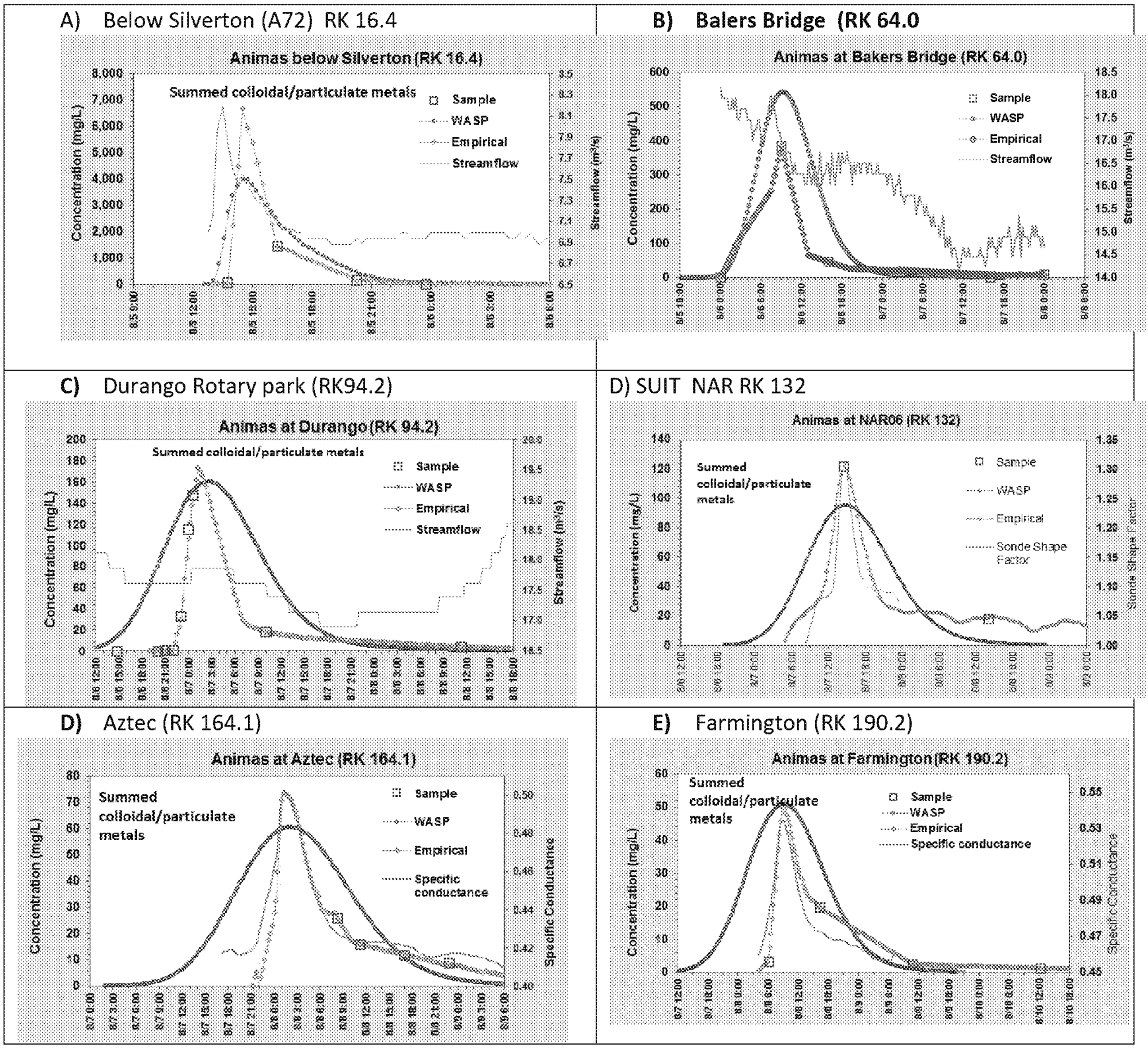

Figure 4-13. Examples of plume reconstruction by GKM WASP and the empirical model for sites on the Animas River. RK is distance from the Gold King sources in kilometers. Each site shows the empirical model and WASP concentration predictions and some independent parameter used at the site to help guide reproduction of the plume shape. This was usually flow at upper Animas sites and continuous sonde data at middle and lower Animas sites. A) below Silverton (A72) at river kilometer 16.4; B) Animas River at Baker's Bridge at river kilometer 64; C) Animas River at Durango at river kilometer 94.2; D) Animas River on the Southern Ute Indian Tribe site NAR06 at river kilometer 132; E) Animas River at Aztec at river kilometer 164.0 and E) Animas River at Farmington near the USGS gage at river kilometer 190.2.

A) Gold King plume passing through the confluence of Animas River (left) and San Juan River (right) at Farmington

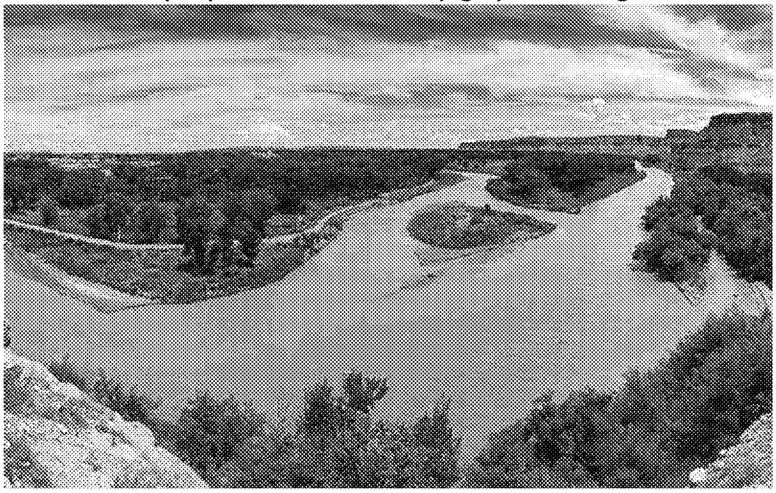

Photo: Theamericanenergynews.com

B) Middle San Juan River during time of Gold King plume travel.

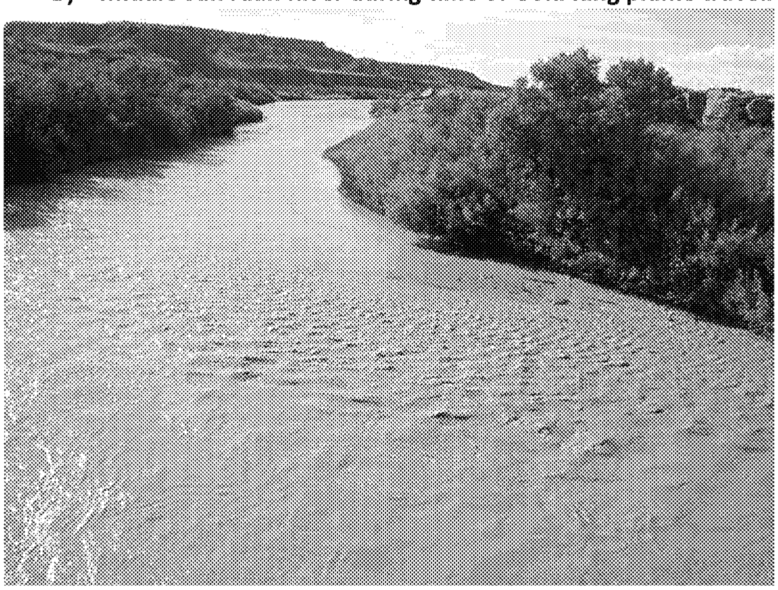

Photo: UDEQ

Figure 4-14. The San Juan River during the Gold King plume. A) As plume flowed into the river at its confluence with the Animas River at Farmington (photo from theamericanenergynews.com). B) At Montezuma Creek at river kilometer 346.

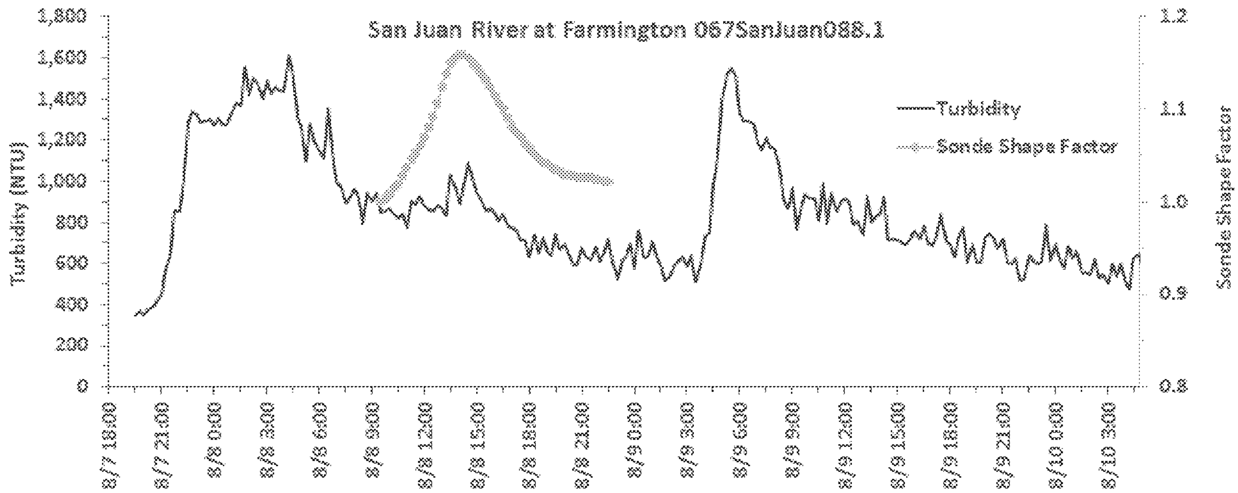

Figure 4-15. Establishing Gold King plume movement in the San Juan River. High background sediment level and turbidity obscured visibility of the plume as it traveled westward from Farmington. Streamflow was complex during plume passage due to release of water from the Navajo Dam. The timing of plume passage was established by GKM WASP and a sonde operated by NMED. The sonde rise and fall is shown by imposing the sonde shape as illustrated in Figure 4-5 with peak. A small rise in turbidity appeared to confirm estimated timing. Turbidity was also clearly responding to other factors during the 3-day time period shown in the turbidity trace.

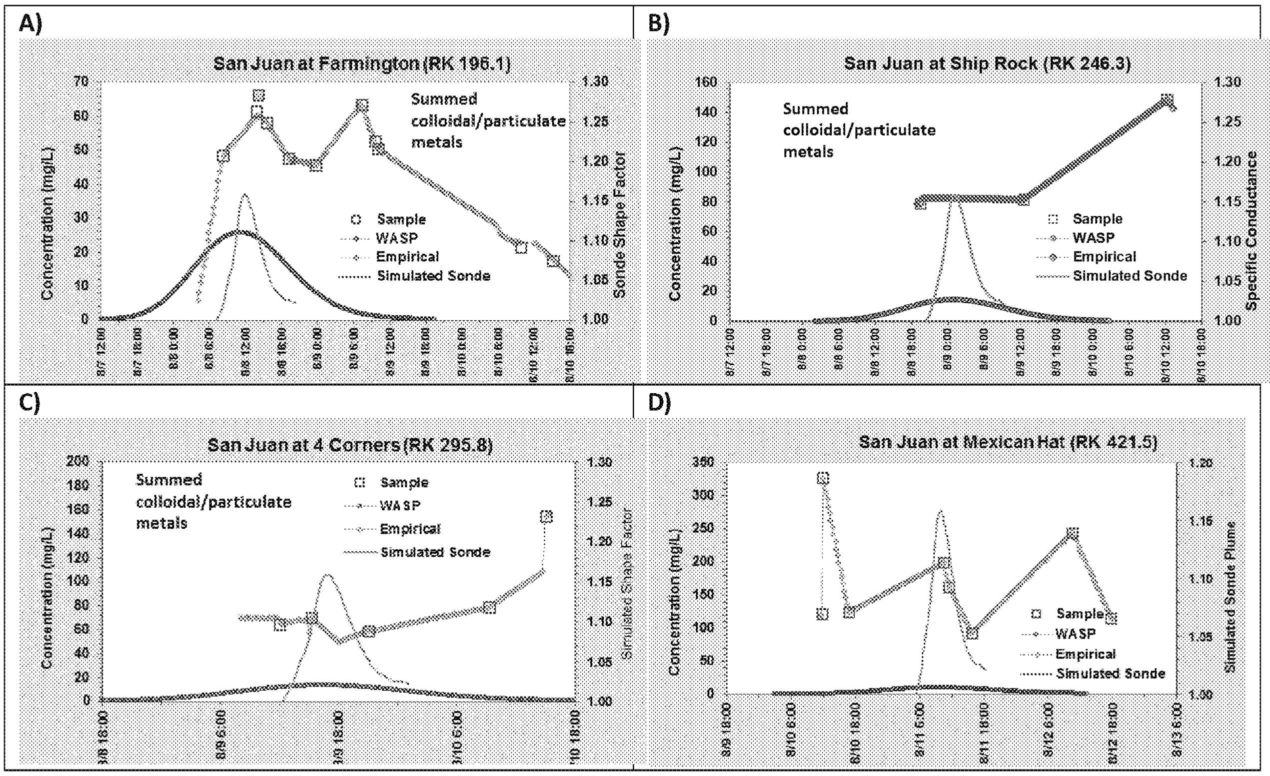

Figure 4-16. Examples of plume reconstruction by GKM WASP and the empirical model. A) San Juan River at Farmington at river kilometer 196.1; B) San Juan River at Shiprock at river kilometer 246.3; C) San Juan River at 4 Corners at river kilometer 295.8; D) San Juan River at Mexican Hat at river kilometer 421.5.

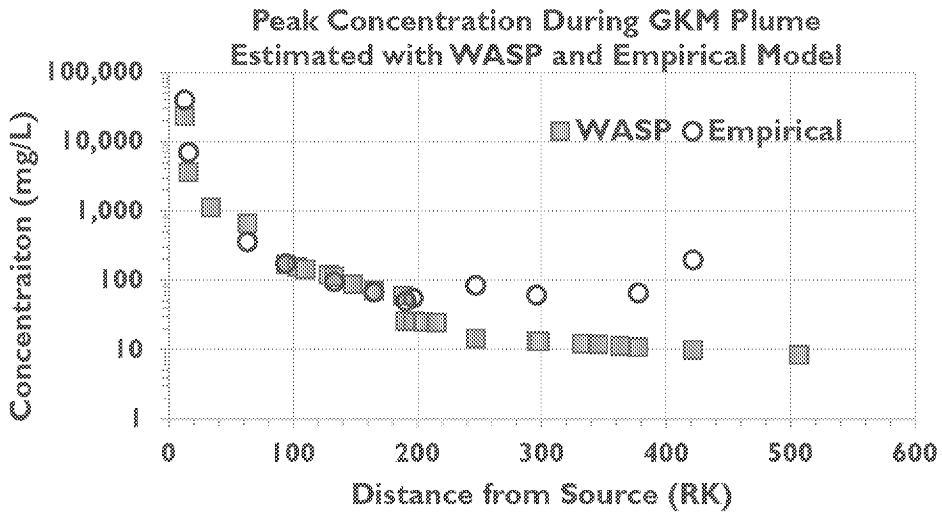

Figure 4-17. Peak concentration of summed metals as a function of distance from the Gold King source in the headwaters of the Animas River. Metals concentrations declined sharply in the first 100 km of travel and within the Animas before joining the Animas at river kilometer 191.9. The empirical model that tracks observed water concentrations increased through the San Juan as sediment increased. WASP models the system without background metals and showed the plume slowly declining before joining Lake Powell at river kilometer 550.

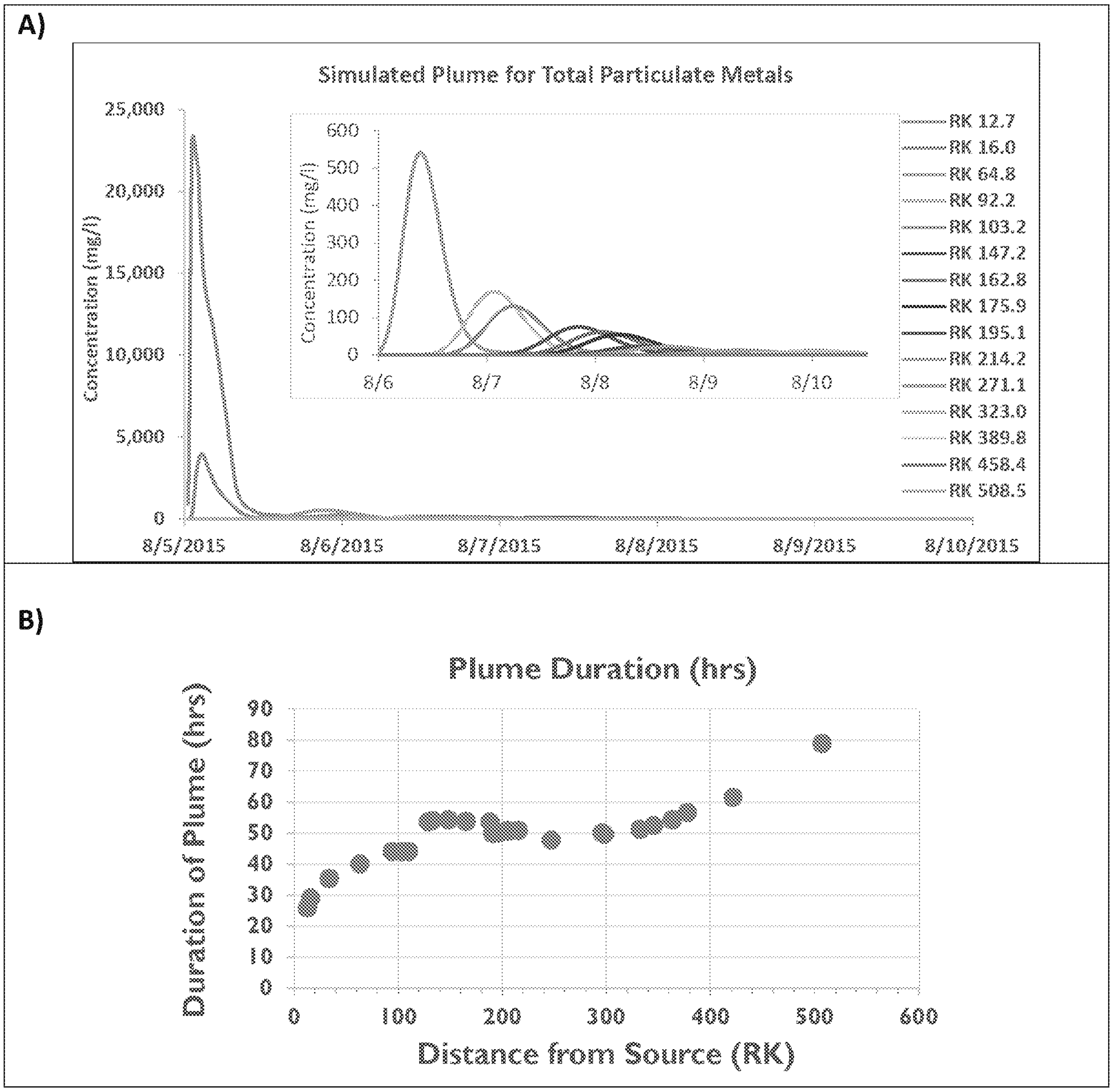

Figure 4-18. A) Simulated Concentrations for Total Metals. Total metal concentrations plotted versus time for different river distances. Inset figure zooms in to concentrations. Total metal concentration is seen to decrease over time and spread out. This figure shows the effects of dilution, settling, and dispersion. The peak concentration decreases over time, and it takes longer and longer for the plume to pass by a location. Each individual line represents a single location. If one were to stand at a given river distance, then for the duration of time on the x-axis, that person would see the rise and fall of the concentration of metals over time. The curve is not quite a normal distribution, as every curve has a quicker rise in the beginning (sharper ascent on the left of the peak) and a slower decline (a trailing tail on the right of the peak). B) Duration of the plume in hours modeled by GKM WASP as a function of distance from the Gold King Mine source. GKM WASP plume duration increases due to dispersion and drag forces. The empirical model estimates plume duration within a narrower 10-40 hour range based on observational evidence.

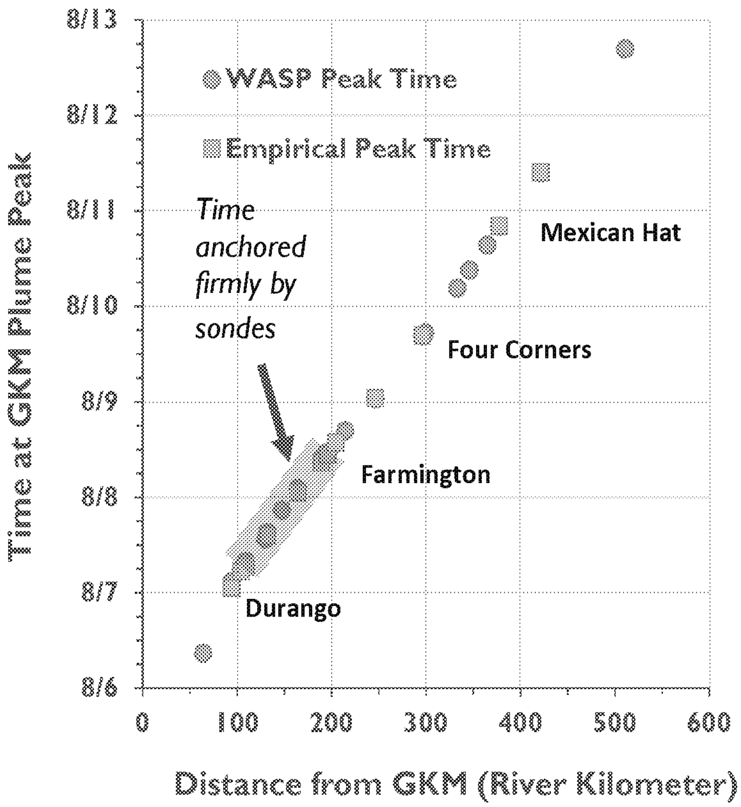

Figure 4-19. Tracking of the Gold King plume peak arrival by distance from the Gold King source. GKM WASP tracks flow and velocity at approximately 2-km increments. The empirical model establishes plume peak at twelve locations using a variety of evidence including GKM WASP estimates. Plume travel in the San Juan was difficult to establish with observations due to turbidity.

Table 4-4. Plume duration and travel time to peak concentration for different locations along the Animas and San Juan Rivers determined from the GKM WASP model. This table presents travel time statistics for sites ordered by distance from the Gold King Mine. The plume duration is defined as the time for 99% of the plume to pass, centered at the peak concentration. The peak concentration is the highest concentration simulated by WASP. The plume duration lengthens as it travels downstream due to mechanical dispersion. The plume arrived at the Utah DEQ's Clays Hill Ramp 7.2 days after the release occurred and required 3.3 days to fully pass.

River Distance (km)	Site	Plume Duration (d)	Time to Peak Concentration (hr)	Estimated Time at Peak
12.54	Cement Creek	1.0	0.7	8/5/15 13:19
16.4	Animas at Silverton	1.0	2.2	8/5/15 14:45
33.8	USGS gage at Tacoma	1.2	9.6	8/5/15 22:11
63.8	Animas at Baker's Bridge	1.3	20.6	8/6/15 9:12
94.2	Animas at Durango	1.6	38.1	8/7/15 2:43
104.0	So Utes AR19.3	1.6	41.3	8/7/15 5:51
109.0	So Utes AR16	1.6	42.9	8/7/15 7:30
129.6	USGS at Cedar Hill 9363500	1.7	49.4	8/7/15 13:59
132	SoUtes NAR06	1.7	50.4	8/7/15 14:58
147.5	ADW 022	1.7	55.7	8/7/15 20:15
164.1	At Aztec ADW 010, NM66Animas028.1	1.8	61.6	8/8/15 2:13
189.4	NMED 66Animas001.7, FW 040	1.8	68.6	8/8/15 9:10
190.2	Animas at Farmington (FW040)	1.8	68.6	8/8/15 9:10
196.1	San Juan at Farmington (FW020)	1.8	70.0	8/8/15 10:37
196.9	San Juan at LP	1.8	70.0	8/8/15 10:37
204.4	NM 67SanJua088.1	1.9	72.4	8/8/15 13:01
204.5	LVW-030	1.9	72.4	8/8/15 13:01
214.4	SJFP	1.9	75.3	8/8/15 15:53
246.3	SJSR	1.9	83.2	8/8/15 23:48
295.8	SJ4C	2.1	99.1	8/9/15 15:39
298.7	Utah 160 Xing	2.1	100.5	8/9/15 17:04
333.2	SJME	2.2	111.8	8/10/15 4:21
345.7	Utah nr Montezuma	2.3	116.3	8/10/15 8:54
345.8	SJMC	2.3	116.3	8/10/15 8:54
364.8	Utah Swinging Footbridge	2.4	122.6	8/10/15 15:10
377.1	Utah Sand Island	2.4	126.2	8/10/15 18:46
377.6	SJ88	2.4	126.2	8/10/15 18:46
421.3	SJMH	2.7	140.6	8/11/15 9:10
421.5	Utah Mexican Hat	2.7	140.6	8/11/15 9:10
510.7	Utah Clays Hill Ramp	3.3	172.0	8/12/15 16:33